# Space Shuttle Solid Rocket Booster Debris Assessment

United Space Alliance

Kennedy Space Center, FL

## 1.1 How and Why the Project Was Selected

As a subcontractor to NASA, United Space Alliance (USA) is responsible for the day-to-day operations of the Space Shuttle. The loss of the Space Shuttle *Columbia* and crew on February 1, 2003, was a tragic reminder of the potential dangers of manned space flight and had a profound effect on USA's vision of being a "*world leader in space operations on Earth, on orbit and beyond.*"

The Space Shuttle *Columbia* Accident revealed a fundamental problem of the Space Shuttle Program regarding debris. Prior to the tragedy, the Space Shuttle requirement stated that no debris should be liberated that would jeopardize the flight crew and/or mission success. When the accident investigation determined that a large piece of foam debris was the primary cause of the loss of the shuttle and crew, it became apparent that the risk and scope of damage that could be caused by certain types of debris, especially ice and foam, were not fully understood. There was no clear understanding of the materials that could become debris, the path the debris might take during flight, the structures the debris might impact or the damage the impact might cause.

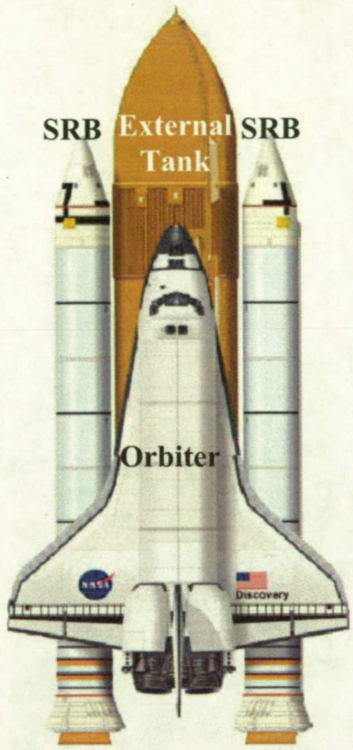



**Figure 1. Space Shuttle**

Because of the accident investigation findings, NASA issued a requirement to all Shuttle Elements, including the Orbiter, External Tank and Solid Rocket Booster (SRB) (Figure 1) to define their debris environment and verify their structural capability to withstand debris impacts. The SRB Debris Assessment team was formed to address the new debris requirements to ensure that the SRBs were safe for the Shuttle's Return to Flight (RTF) by verifying that the SRB hardware would not sustain damage that could potentially lead to catastrophic results if impacted by foam or ice debris. Since no such work had been done before at SRB, a new innovative process had to be created, executed and validated before the Space Shuttle would be allowed to launch again.

## 1.2 How the Team's Project Goal(s) Aligned to the Organization's Goal(s)

In addition to supporting the primary NASA and USA goal of returning the Space Shuttle to flight by understanding the SRB debris environment and capability to withstand that environment, the SRB debris assessment project was divided into four primary tasks that were required to be completed to support the RTF goal. These tasks were (1) debris environment definition, (2) impact testing, (3) model correlation and (4) hardware evaluation. Additionally, the project aligned with USA's corporate goals of safety, customer satisfaction, professional development and fiscal accountability.

<u>Safety</u> – *Provide safe operations for all aspects of our business*

The team focused on safety by verifying that critical SRB hardware would still function as designed after being impacted by debris. If critical components did not function as expected, the safety of the mission and crew could be compromised. The team was encouraged to investigate possible design/process changes that could either improve an unacceptable margin of safety or reduce the risk associated with a debris impact. From an analysis perspective, safe operations are implemented by following a rigorous checking/reviewing process that ensures all analyses are technically sound and accurate. This focus on safety, both in terms of the hardware performance and the supporting analysis, would provide a direct benefit to key stakeholders, USA, NASA and the flight crew, because it would ensure that the SRBs were safe for flight.

Customer Satisfaction – *Achieve excellent customer satisfaction and outstanding quality*

NASA's satisfaction with the work of USA-SRB Element and the team is of the utmost importance. The primary measures of this goal are meeting key milestones to support the Shuttle launch and receiving positive comments and recognition from NASA. The key stakeholders are USA-SRB Element and NASA.

Professional Development – *Be the company of choice for our employees*

USA-SRB Element recognizes that complex engineering problems, such as debris assessment, require a variety of specialized skills only attainable through experience. This project offered team members opportunities to improve their skills and develop their experience base through mentoring, training and leadership development. The primary stakeholders for this goal are USA-SRB Element and the team member's respective organizations because, through this project, team members will become more experienced and knowledgeable with additional capabilities for tackling difficult problems in the future.

Fiscal Accountability – *Provide excellent financial returns to our stakeholders*

Part of the project involved implementing a test program, which can be very costly in terms of acquiring a facility, instrumentation and test articles, as well as analytical and test support personnel and travel costs. This project needed to be carefully managed to prevent unnecessary expenditures in all of these categories. The financial returns of this project can be measured as a cost savings to USA and NASA stakeholders for the work performed, as well as the preservation of valuable flight assets.

### 1.3 How the Team Members Were Selected

Sub-teams were formed to focus on each of the four specific project tasks. This allowed for expertise in each of the four areas and balanced the workload among the team members. The team was also well balanced with individuals skilled in theoretical work and practical application. This helped the team perform more effectively because one portion of the team was able to provide a solid theoretical foundation for the analysis, and others on the team were able to implement those concepts with practical solutions. Two team members served as the overall project leaders to ensure that each of the four individual teams functioned together and did not lose sight of the overall goal.

Team members were selected from three different organizations: Loads and Aerothermal Analysis, Aft Assembly Analysis, and Materials and Processes (M&P), based on their experiences, expertise, problem solving skills and job responsibilities as related to the specific needs for each of the four primary tasks. As part of their normal job function, Loads and Aerothermal Analysis defines loads and environments for the SRB and performs a significant amount of testing. Aft Assembly Analysis performs structural analyses for SRB hardware. M&P works with SRB hardware and thermal protection system materials.

Debris Environment Definition required processing extremely large volumes of data to determine the critical conditions for SRB hardware. Team members had organizational skills for managing the data plus previous experience in writing specialized computer programs for data processing. They were also familiar with all SRB hardware and their applicable loads and environments required for analysis.

Impact Testing required the preparation and execution of the test plan, design of test fixtures and the test set-up, management of facility logistics/scheduling, high-speed video recording and data acquisition/management, and preparation and handling of the debris projectiles and impact targets. Team members had previous experience in testing and instrumentation selection. M&P

had the responsibility for procuring, preparing and instrumenting the test articles and projectiles as well as assessing the post-impact condition of the test articles.

Model Correlation required an understanding of the test configuration and instrumentation, raw test data and the dynamic response of structures. Team members had previous experience working with test data and constructing computer models.

Hardware Evaluation required knowledge of finite element analysis, three-dimensional model construction and an understanding of structural analysis. Many of the team members for this task were new employees selected for their ability to quickly learn new software and analysis techniques.

**2.1 How the Team Identified Potential Changes for Improvement/Innovation**

Foam debris loss and the resulting impacts that occurred without major damage had become so common during Shuttle flights that the impacts were not considered a serious threat to the safety of the Shuttle or crew. The accident investigation report states that:

> With each successful landing, it appears that NASA engineers and managers increasingly regarded the foam-shedding as inevitable, and as either unlikely to jeopardize safety or simply an acceptable risk. The distinction between foam loss and debris events also appears to have become blurred. NASA and contractor personnel came to view foam strikes not as a safety of flight issue, but rather a simple maintenance, or "turnaround" issue.[1]

When the accident investigation team performed impact testing with foam blocks they arrived at a surprising result. In complete contrast to many of the pre-existing beliefs about the dangers of foam debris, these impacts caused significant damage to the Shuttle and confirmed that the foam debris impact was the cause of the accident. Therefore, it was evident that NASA needed to develop an innovative process to address the newly identified debris risk.

With the new debris requirements, NASA developed an engineering process that outlined the numerous steps that were needed to understand the debris environment and Shuttle capability in order to safely return to flight. At a minimum, NASA required all Shuttle Elements perform impact testing and build computer models to validate the impact test data. The specifics for what needed to be done and how it should be accomplished were left up to each Shuttle Element.

Research indicated that previous debris impact assessments had only addressed low-velocity liftoff debris by drop-testing simulated ice balls on flat panels. These previous tests did not address the potential for high-velocity impacts of ice or foam debris during flight. High-velocity impacts would require the development of appropriate tools such as detailed dynamic models to support testing and analysis. The team realized that the entire process had to be developed from the ground up, and focused on four primary tasks necessary for evaluation.

The team used a variety of tools to develop a process for the SRB Element debris evaluation. Team members attended technical interchange meetings within the Shuttle debris and analysis communities to brainstorm, exchange ideas and share lessons learned on various processes and procedures for each of the tasks. Data gathered at these meetings were analyzed and evaluated to determine if the analytical techniques or methodologies being used by other Elements could be applied or adapted to the SRB Element process that was being developed. Since the Orbiter Element had performed impact testing during the accident investigation, SRB took advantage of lessons learned in key areas, such as how to fire a projectile to reach the desired velocity. Additionally, the team conducted trade studies to evaluate various software tools to assist with the four tasks.

[1] "Columbia Accident Investigation Board Report," Volume 1, August 2003.

## 2.2 How Potential Changes were Evaluated and How the Final Change Was Selected

The SRB Element determined that NASA's new debris requirements could be satisfied by focusing on four primary tasks: debris environment definition, impact testing, model correlation and hardware evaluation. The debris environment definition identified potential debris impacts to SRB hardware. Impact testing reproduced the predicted debris impacts by using an air-cannon to fire projectiles at high speeds at test targets. Model correlation used computer models to reproduce the impact test results, and hardware evaluation determined if the SRB hardware could survive a debris impact. The potential change being evaluated was a process the team developed that inter-connected each of the four tasks and is shown in a flow diagram (Figure 2). Within each of the four tasks, several process options were evaluated before selecting the final process.

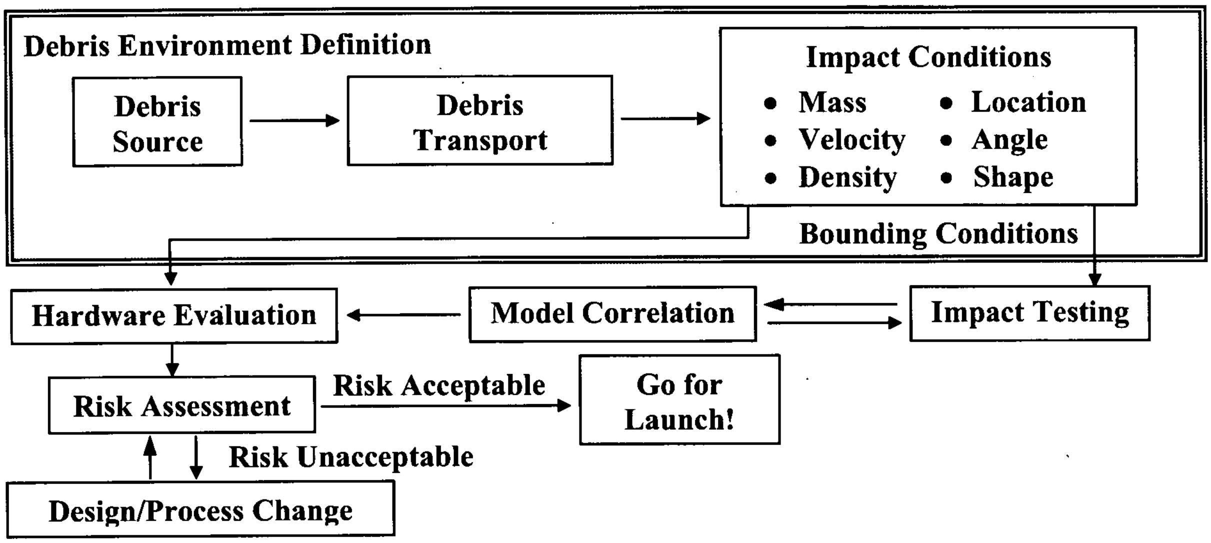



**Figure 2. Debris Assessment Tasks Process Flow Diagram to Support Return to Flight**

The debris environment definition came from an extensive list of potential debris sources that NASA down-selected to the sources with the greatest threat to the Shuttle vehicle (primarily ice and foam). These debris sources were evaluated with a modeling process, Debris Transport Analysis (DTA), that determined how the debris would travel after it was liberated and where the debris might impact. The results produced impact conditions that included the location, velocity and energy of the debris particle at the time of impact. A trade study would be needed to evaluate software tools that would be required for processing the debris results.

Impact testing results from the Orbiter Element and additional data analysis indicated that the greatest debris threat to the Shuttle would be from ice and foam debris, and SRB needed to implement a test program for those materials. Through a selection process that included identifying potential test facilities, requesting vendor proposals, conducting on-site visits and witnessing demonstration tests, one facility was selected for foam testing and another was selected for ice testing. This allowed testing of both projectiles to be conducted simultaneously and saved a considerable amount of time, an important factor to minimize the delay in returning the Shuttle to flight.

For the model correlation and hardware evaluation tasks, the team determined that the software currently in use by USA would not be adequate for the project because it could not sufficiently perform the high-speed dynamic analyses that would be required. An additional trade study would be needed to evaluate new software to find one that would best suit the needs of the team.

### 2.3 How the Final Change was Validated

Since the change being implemented was a process, the validation was based on the effectiveness of that process to produce useable results and meet the needs of each task. The team identified the key products that would be generated by each task. Each task product was an input that was required to perform another task; therefore, team members performing each task were considered to be customers for the data products produced by the other tasks. A flow diagram identifies the tasks/customers in the circles and the products in the rectangles (Figure 3). The team also recognized that each customer would need to be involved in specifying the format of the data product they were to receive so it would best meet their needs and reduce the risk of misinterpretation of the data.

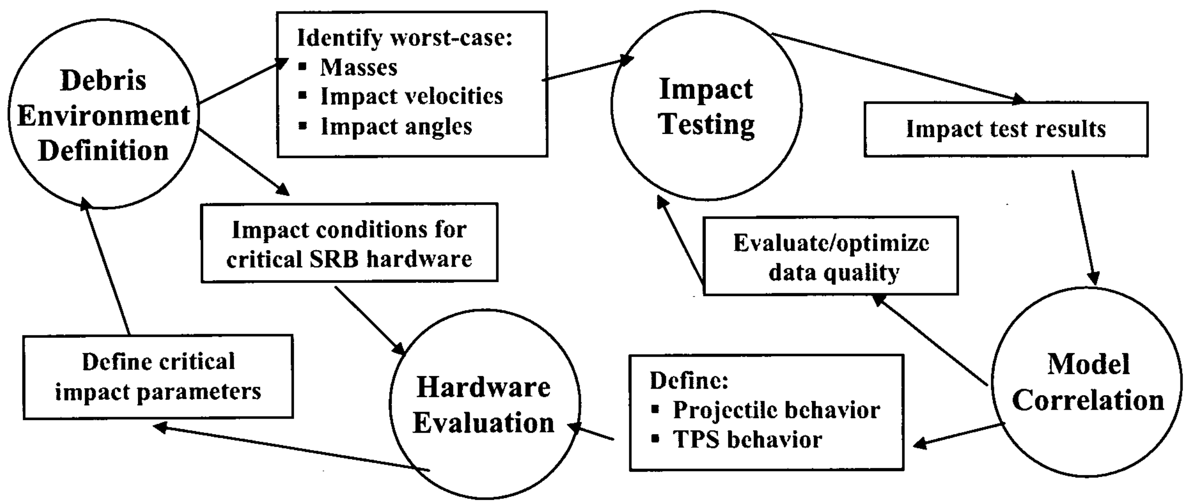



**Figure 3. Debris Assessment Product/Customer Flow Diagram**

Debris Environment Definition – Team members that evaluated the debris environment data were responsible for providing results to support both the impact testing and hardware evaluation tasks. The impact testing task required data that included the worst-case masses, impact velocities and impact angles for use in the development of test plans. The hardware evaluation task required data specific to each of the critical components that required analysis. Team members performing the hardware evaluation needed to identify the parameters that produced the worst-case impact conditions to assist with the filtering of the debris environment data.

Impact Testing – Team members that performed the impact testing would need to take the worst-case debris environment conditions and develop a test program to impact targets with foam and ice projectiles. Data from these tests would be provided to team members performing the model correlation. In consideration of the model correlation task requirements, the impact testing defined the camera set-ups with multiple fields of view, frame rates and image resolutions to capture the projectile behavior for the use in the model correlation.

Model Correlation – Team members that performed the model correlation would need to work closely with team members performing the impact testing to assist in the evaluation of data quality and adjust test conditions to optimize the data quality. Having good quality data from well-defined target locations was essential to reproducing the test results with the computer models. To support the hardware evaluation task, the model correlation task needed to define the behavior of the projectile as it impacted the target and the behavior of the thermal protection system as it failed due to the debris impact. (The thermal protection system (TPS) is a thin layer

of material, such as cork, used to protect the underlying SRB metallic structure from high temperatures during flight).

Hardware Evaluation – Team members that performed the hardware evaluations used the projectile and TPS behavior at impact to perform studies to evaluate parameters, such as projectile orientation, impact location, impact angle and impact energy, that would produce the worst damage to a specific structure. The key parameters that had the greatest effect on impact damage were identified and provided to the debris environment definition task as parameters used to sort the debris environment data.

### 3.1 How Potential Courses of Action for Improvement/Innovation Were Identified

Once the team developed a process that identified the tasks that needed to be performed, the team proceeded with evaluating potential courses of action to implement the debris assessment process. Each of the four tasks had multiple solutions that were considered. The team used criteria, such as previous experience with similar problems, current knowledge/skill base, consultation with peers, and trial and error, to help establish the process for each task. The course of action for each task considered the product that would need to be produced as well as made sure that the needs of the customer and stakeholder were taken into account. The specific course of action selected for each task was based primarily on the skills of the team members selected to perform each task.

### 3.2 How the Potential Courses of Action Were Evaluated and How the Course of Action Was Selected

For each task, all potential courses of action that were identified would serve to provide the data necessary to determine the integrity of the hardware and provide launch support. Each potential course of action required evaluation to determine which would prove to be the best method to acquire the desired capabilities and tools while still meeting launch milestones.

Debris Environment Definition – Based on previous programming experience, team members considered several different commercial off-the-shelf (COTS) software applications such as Microsoft Excel, MATLAB, FORTRAN and C++ for processing the debris environment data. A trade study using the key parameters for the data analysis was performed (Figure 4). The data was not formatted in a way that could easily be read by MATLAB, and the majority of files were too large to be loaded into Excel directly; therefore, the team chose to use a combination of FORTRAN and Excel to process and filter the data. This course of action worked well because, at the time the FORTRAN code was written, the hardware that was going to be evaluated had not been selected. The FORTRAN program was used to sort the data for each of the major SRB structures, making the file sizes small enough to be read by Excel. Then the data was further filtered to find impacts for specific components, by various impact parameters.

| Parameter | Software Application | | | |
|---|---|---|---|---|
| | Excel | MATLAB | C++ | FORTRAN |
| Read file format | | | X | X |
| Handle file size | | X | X | X |
| User familiarity | X | X | | X |
| Ease of use | X | | | |
| Easily modifiable | X | | | |

**Figure 4. Debris Environment Software Trade Study**

Model Correlation – The team identified model correlation as a specific task in the process, however, since the team had no previous experience with high-speed impacts, it was not known whether computer models could be built and correlated to the test data. Therefore, one potential

course of action was to conduct impact tests on all of the critical SRB hardware. A second course of action was to conduct limited testing that would provide enough information to conduct correlation studies and allow for the construction of computer models that could accurately simulate the impact events. A comparison of each option was performed (Figure 5). The test only approach had the desirable aspect of physical test data for the hardware, but the data would be limited to the instrumentation locations and specific impact parameters (e.g. projectile mass, velocity, angle and location). The test/model approach would provide data for the entire structure and allow for variation in the impact parameters. The costs for both approaches would include hardware, test fixtures, data acquisition equipment and support personnel, but would be significantly more expensive for the test only approach. The team chose to proceed with the test/model option because it produced significantly more benefits than the test only option.

| Test Only | Test/Model |
|---|---|
| Data limited to: | Data Extended to: |
| - Tested hardware | - Entire structure |
| - Instrumentation locations | - Any location |
| - Specific impact parameters | - Various impact parameters |
| Requires significant flight assets | Requires limited flight assets |

**Figure 5. Comparison of Model Correlation Options**

Impact Testing – For impact testing, the team had three potential courses of action for the test targets (Figure 6). The testing could consist of only flight hardware, only flat panels or a combination of both. The team performed an analysis and determined that flat panels could be used to adequately represent the behavior of large SRB structures. Therefore, the majority of the impact testing was performed on flat panels. While the flat panel data was used for calibrating the computer models and as a verification of that calibration, some test data from flight hardware was also needed. Four SRB components were selected for impact testing because each had a critical function that had the potential to compromise flight safety if the hardware could not withstand a debris impact. Additionally, these components had either a complex geometry or a less common TPS material for which models were not readily available, making it difficult to have confidence in model results without validation from test data.

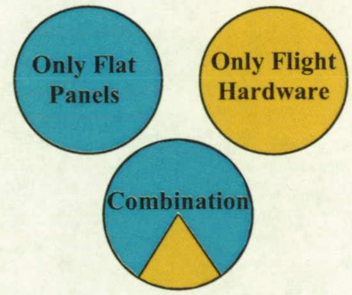



**Figure 6. Impact Testing Options**

Hardware Evaluation – As mentioned previously, the current software tools for hardware analysis were not adequate for the high-speed debris impacts. The model correlation and hardware evaluation teams evaluated several industry standard COTS software packages including LS-DYNA, MSC Dytran and ABAQUS Explicit for use in the dynamic analysis. LS-DYNA was selected for its efficiency and robustness. Additionally, LS-DYNA was compatible with ice and foam models that had been developed by the Orbiter Element. Another benefit was that a significant amount of model data from existing SRB static structural models could be imported into LS-DYNA allowing the dynamic models to be created much faster.

### 3.3 How the Final Course of Action Was Validated

Debris Environment Definition – The final course of action for this task was validated by the ability of team members to deliver data to the hardware evaluation team in a timely manner. Team members processed the nine GB of data with the FORTRAN code once, and used the results to establish large databases for all of the foam and ice impacts to each of the five major SRB structures. It would have been possible to write a very specialized FORTRAN program to process all of the data for each SRB component; however, the course of action selected was validated as the best solution as new components were considered for analysis. With the

database available, the extremely time consuming process of dealing with all of the data was not necessary. By filtering the databases in Excel, the team was able to take millions of SRB impacts and produce the critical impact conditions on a component within a few hours.

Impact Testing – The final course of action for this task was validated by the ability of the test to produce quality data for the model correlation team. Since the analysts performing the correlation took an active role in the real-time processing of the test data, changes to the test set-up and instrumentation could be incorporated to improve the data quality. For example, during testing of an SRB component, the number of measurements was increased from four to twelve based on recommendations from the analysts for additional data at specific locations. In another case, the analysts noted poor data quality and recommended a modification to the component's mounting structure that provided additional stiffness and improved the data.

Model Correlation – Following the decision to implement the combined testing and modeling approach, the team set out to verify the effectiveness and accuracy of that course of action. In fact, a method to verify model results and establish their accuracy and validity was built into the plan through model correlation. Model correlation used the data collected during impact testing to perform an analysis with computer (or mathematical) models built to simulate the impacts from the testing. A comparison was made between the analytically generated behavior of the system to the test measured physical behavior of the system. By performing correlation studies, the mathematical models could be adjusted and relevant material parameters could be established to accurately predict both the response of the impacted structure and the behavior of the debris projectile. Once the appropriate material parameters were established, they were then used to model other structures.

The test set-up allowed for rigorous control over projectile parameters such as impact angle, velocity, and projectile orientation, and data were recorded from several combinations of the parameters for the various targets. Each test shot attempted to record several video angles, strain gage, accelerometer and load cell readings which allowed for a thorough understanding of the behavior of the projectile as well as the structural and TPS response of the impacted target.

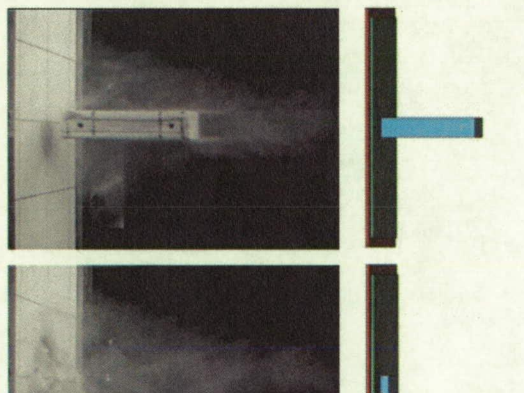


Figure 7. Test and LS-DYNA Model Simulated Impact

The flat panel tests were used to generate the appropriate material and modeling techniques that would be necessary to model the subsequent flight hardware. Test photographs showing a foam block impacting a flat panel were compared to an LS-DYNA computer simulation of the same event (Figure 7). Plots that represent a strain measurement recorded on the panel during the foam impact as well as the strain response predicted by the LS-DYNA computer simulation were created (Figure 8). Note that the curves are the same general shape, and the strain values from the simulation are nearly identical to the peak strain response measured during the impact test. This indicates that the computer simulation can accurately reproduce the structural response of the panel to a foam impact.

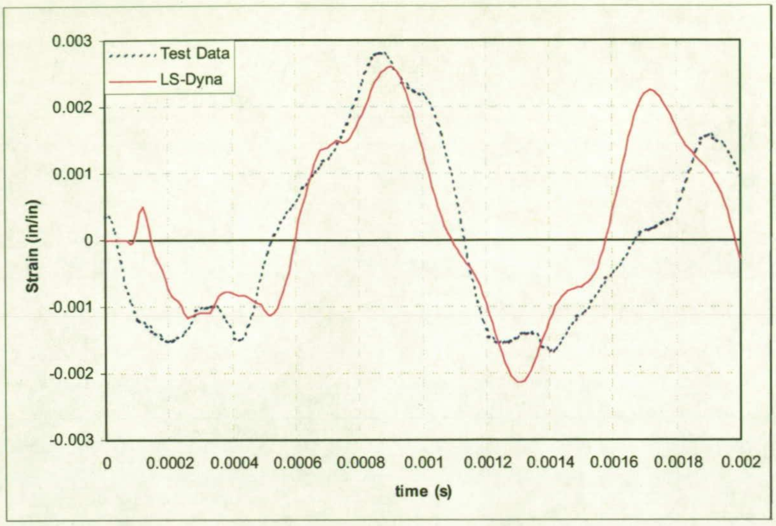
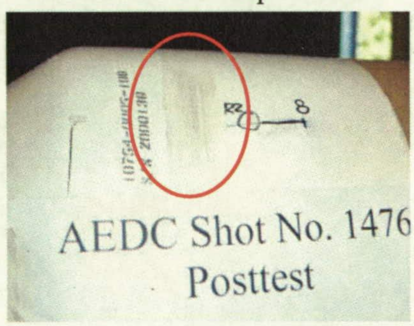



**Figure 8. Test Measured and LS-DYNA Model Simulated Strain Response**

Once it was validated that computer simulations could accurately reproduce the impact behavior for a flat panel, additional models were built of selected SRB hardware to verify that the results could be extended to represent an arbitrary configuration. The post-impact comparison between the test data and LS-DYNA model simulation for the SRB Upper Strut Fairing indicate the same dent depth for a foam impact and show an example of hardware correlation (Figure 9). Test photographs showing a foam block impacting an Upper Strut Fairing were compared to an LS-DYNA model simulation of the same event and demonstrate how LS-DYNA was used to predict the behavior of the impacted structure (Figure 10). Similar to the flat panel test, the strain response predicted by LS-DYNA showed good agreement with the data recorded on Upper Strut Fairing during testing.

Measured Dent Depth: 0.43 in




Model Predicted
Dent Depth: 0.43 in

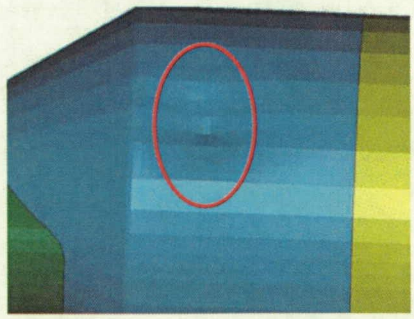


**Figure 9. Upper Strut Fairing Test Measured and LS-DYNA Predicted Deformation**

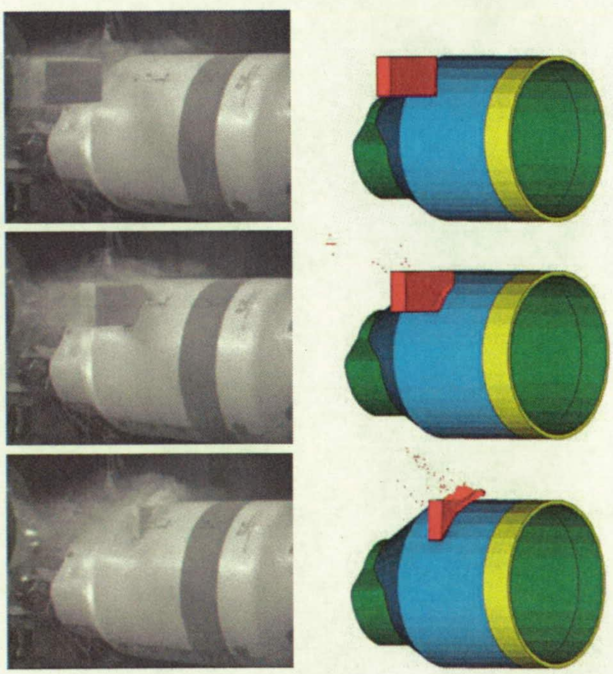


**Figure 10. Upper Strut Fairing Test and LS-DYNA Model Simulated Impact**

The primary goal of this project was to support the RTF debris effort. There were many tangible and intangible benefits to the NASA and USA-SRB Element stakeholders. Throughout this project, the SRB Element was recognized by NASA as a pace-setting organization and earned respect from other Shuttle Elements for their work. The results of the analysis established the NASA stakeholder's confidence in the techniques that were used and the capability of USA-SRB Element to succeed in solving difficult problems. The debris efforts were a significant contribution to RTF providing all of the stakeholders with a sense of accomplishment and increased morale for being able to do their part in getting back to the business of space flight. Within USA-SRB Element, the project fostered a sense of camaraderie and taught valuable lessons on teamwork and customer focus. All of the team members gained valuable engineering experience that would have taken much longer than the length of this project to obtain under "normal" working conditions.

It is clear from the validation of the course of action for each process that the SRB debris environment can be defined and the SRB capability to withstand debris can be determined. The debris data processing techniques were verified to supply the hardware evaluation team with the required environment. The hardware evaluation team verified that the SRB hardware capability to withstand debris impacts could be determined from dynamic models that had been correlated to test data. Therefore, it can be concluded that the final course of action will result in the accomplishment of the project's goals.

### 4.1 How the Course of Action Was Implemented

An area for potential resistance came from NASA concerns about the team's inexperience. The team was attempting an aggressive high-speed impact testing and modeling project in an area where they had very little experience and a very tight schedule. Fortunately, because of proven competency with previous projects, NASA had enough confidence in the team to continue with the project. NASA's concerns probably led them to take a more active role in the project than would be typical, and their involvement had the potential to cause resistance from team members who felt that the customer might have been overstepping their bounds. The team proved themselves very capable in this task and developed a more cooperative attitude with the customer.

The stakeholders were extremely involved in all aspects of the project, making it very easy to achieve stakeholder buy-in. USA-SRB Element and our NASA customer attended numerous meetings and reviews conducted by the Space Shuttle Program managers to ensure that all Shuttle Elements worked together to achieve the RTF debris objectives. The debris environment definition and use of debris environment data were strongly supported by NASA, and all of the data had buy-in from the appropriate technical communities prior to its release to the Elements.

The Space Shuttle Program management selected four potential facilities that could be used to conduct the impact testing, and stakeholders from the USA-SRB Element and NASA toured each facility to find the one that would best suit the project's needs. The impact test plans were thoroughly reviewed by USA-SRB Element and NASA stakeholders for buy-in. Once approved, the plans were submitted to the Space Shuttle Program managers for final approval that was required before testing could begin. Stakeholders from NASA and USA-SRB Element were on-site during testing and actively involved in the implementation of the test plan.

In addition to vendor supplied training, team members participated in LS-DYNA training sessions that were conducted by NASA. The model correlation approach used by the team was thoroughly reviewed and approved by NASA and Space Shuttle technical communities. The hardware evaluation results were presented to USA-SRB Element and NASA stakeholders for buy-in prior to taking the results forward to the Space Shuttle Program managers. Some of the

approaches and results were met with some resistance at NASA as the validation process was questioned. These issues were quickly resolved with subsequent in-depth discussions between team members and concerned parties.

### 4.2 What Results Were Achieved

Each of the four tasks on this project produced measurable results. The debris environment definition task produced data for thirty critical SRB components, satisfying the goal of defining the SRB debris environment. The impact test task completed thorough test programs for ice and foam debris, providing data to the model correlation team. The model correlation task verified that the dynamic models built with LS-DYNA could be used to reproduce the test data. The hardware evaluation task determined the structural capability for thirty components to withstand debris impacts. For each component, the team built an LS-DYNA model, determined the critical impact location and critical projectile orientation for ice and foam debris, analyzed TPS failures, and verified the component's functionality against several criteria. The analysis showed that while some components may receive damage, none would fail to function as required through SRB separation. Some results of the hardware evaluation are presented below.

The Bolt Catcher was selected as a critical component because it retains half of the Forward Separation Bolt that attaches the SRB to the External Tank and is broken by the firing of pyrotechnic charges at SRB separation (Figure 11). The accident investigation identified that the Bolt Catcher might not be strong enough to retain the bolt half, and the assembly was redesigned. The LS-DYNA model shows a foam projectile impacting the Bolt Catcher, and the picture on the right presents the dynamic analysis results (Figure 12). The red area indicates the area with the highest impact stresses, where the most significant damage is most likely to occur.

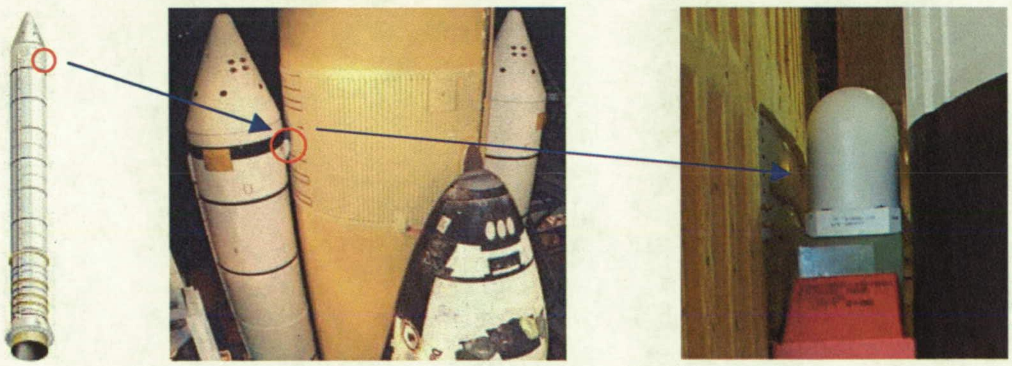


**Figure 11. Bolt Catcher Location**

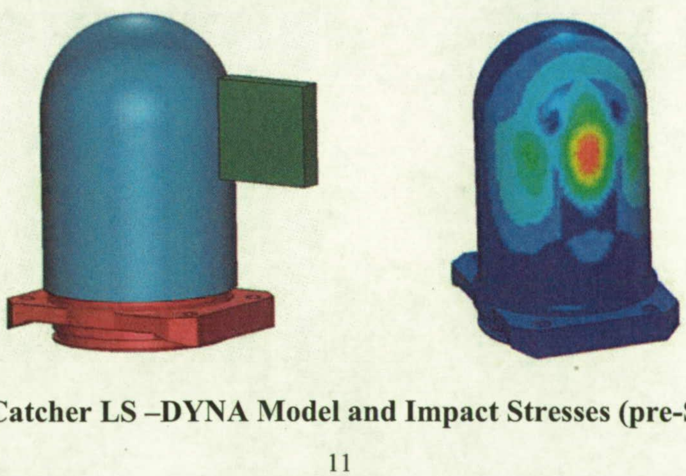


**Figure 12. Bolt Catcher LS –DYNA Model and Impact Stresses (pre-SRB Separation)**

The aft Integrated Electronics Assembly cover was selected as a critical component because it houses the integrated electronics assembly that is used to send commands to the separation bolts and Booster Separation Motors at SRB separation (Figure 13). If these commands are not properly relayed through the integrated electronics assembly, the SRBs might not separate as required. The LS-DYNA dynamic model and results are presented in the same format as the Bolt Catcher example (Figure 14).

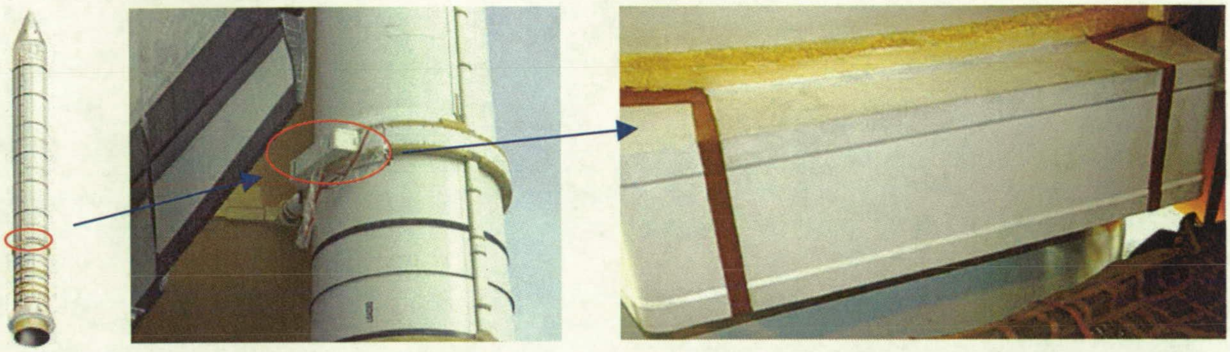


**Figure 13. Aft Integrated Electronics Assembly Cover Location**

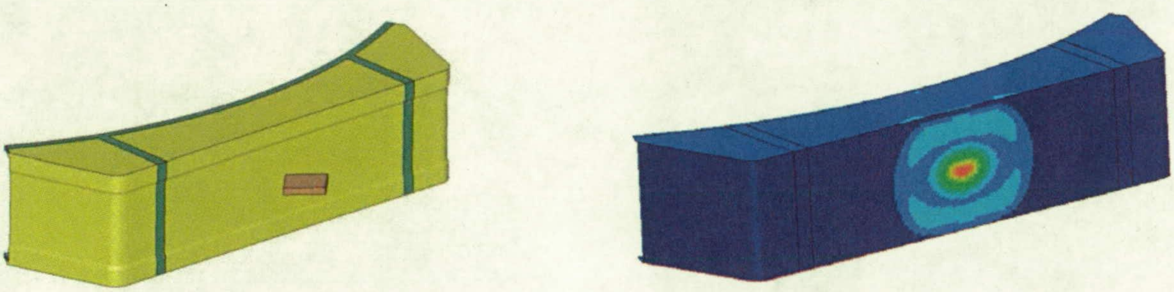


**Figure 14. Aft Integrated Electronics Assembly Cover LS-DYNA Model and Impact Stresses**

The aft Booster Separation Motor nozzle was selected as a critical component because the motors fire at SRB separation to push the SRBs away from the rest of the Shuttle (Figure 15). If an exit cone is damaged, the motors might not fire as expected and the separation might not occur as required. The LS-DYNA dynamic model and results are presented in the same format as the previous examples.

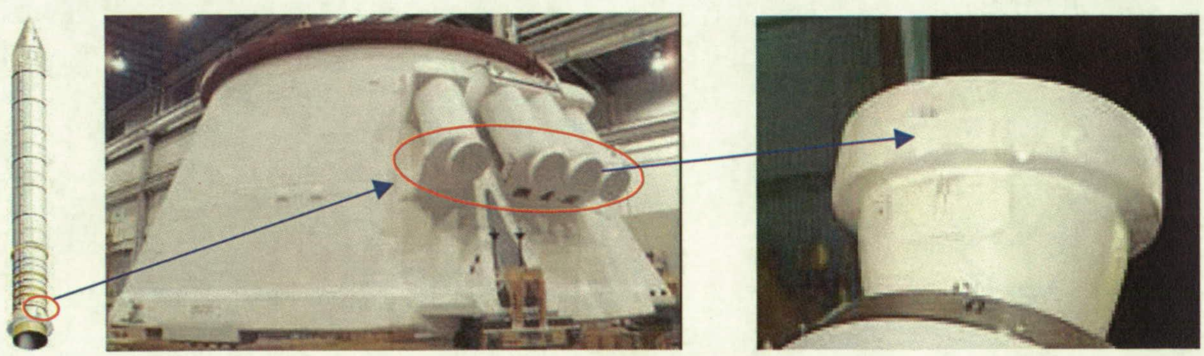


**Figure 15. Aft Booster Separation Motor Nozzle Location**

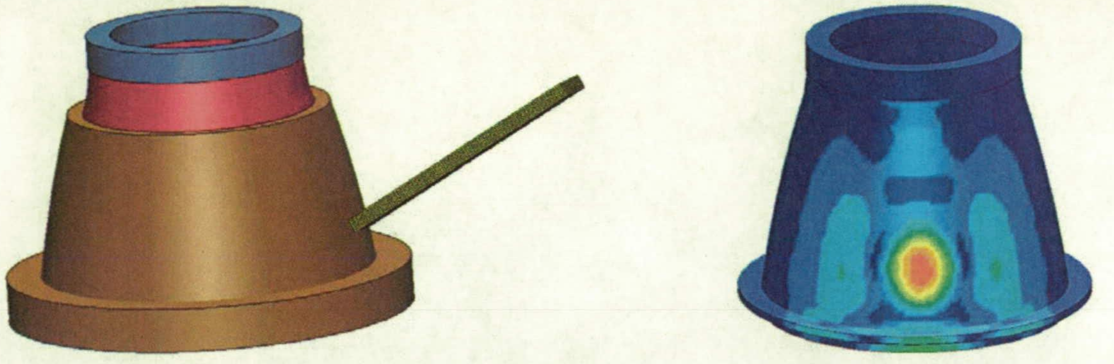


**Figure 16. Aft Booster Separation Motor Nozzle LS-DYNA Model and Impact Stresses**

This project resulted in several significant improvements over time. Obviously, since no analysis was in place when this task began, the successful completion of the project is a significant improvement in the data that is available to make informed decisions regarding the potential debris risk. Once the four primary tasks were completed, the team went above and beyond the requirements and recommended four design changes that could be made to enhance Space Shuttle safety and further reduce the risk to SRB hardware and flight crews. After the thirty most critical SRB hardware components had been analyzed, the team looked for other ways to use the tools that had been developed. The dynamic modeling techniques were used for several components that do not have a function that is critical to flight safety such as the three components illustrated above. Some of these additional components were considered because a foam or ice impact could potentially liberate material on the SRB that then had the potential to impact other parts of the Shuttle.

Another improvement that helped to exceed the team's original goals was the development of a quick assessment tool that could be used for analysis of potential debris sources on launch day. Without this tool, USA-SRB Element would have no way to quickly determine if a potential debris source could pose a safety risk to SRB hardware and a launch scrub or delay could result. The "real-time tool" used for launches as wells as launch simulations was developed after all of the critical SRB components were evaluated with the provided debris environment data. This tool is contained in an Excel database that is divided into three sections. The first part of this database identifies the debris source based on material type (ice or foam), dimensions and the location on the vehicle where it is released. The second part defines the debris environment, where the debris source is characterized and the impact energy is determined at different times during flight to find the critical impact time. The last part of the database contains the structural capability of each SRB component to withstand a foam or ice impact and uses the information from the second part to determine whether the component is able to survive the predicted impact condition. This tool gives USA-SRB Element the ability to perform a comparative analysis for all of the components and make a go/no-go decision for launch in a manner of a few minutes.

The type of analysis that can be performed with the launch tool is shown for the four components previously discussed in this report (Figure 17). The component names are listed on the bottom of the plot along with bars indicating capability in terms of expected debris energy levels. The blue and yellow horizontal lines represent the predicted energy levels for the ice and foam debris, respectively. These values would be calculated based on the debris size, shape and location on the vehicle as identified by the debris inspection team either during a launch simulation or on launch day. The blue and yellow vertical bars represent the component's capability in terms of kinetic energy to withstand ice or foam debris impacts, respectively. Therefore, it can be seen in that at the given energy levels for foam, all of the components except the Bolt Catcher have a

large margin of capability. The aft Booster Separation Motor (BSM) nozzle and aft Integrated Electronics Assembly (IEA) cover indicate a minimal margin of capability above the predicted ice energy level. The Upper Strut Fairing is right at its ice capability, and the Bolt Catcher could not survive either of the predicted ice and foam impacts. Therefore, if the potential debris sources were predicted to impact the Bolt Catcher, the SRB would be a no-go for launch.

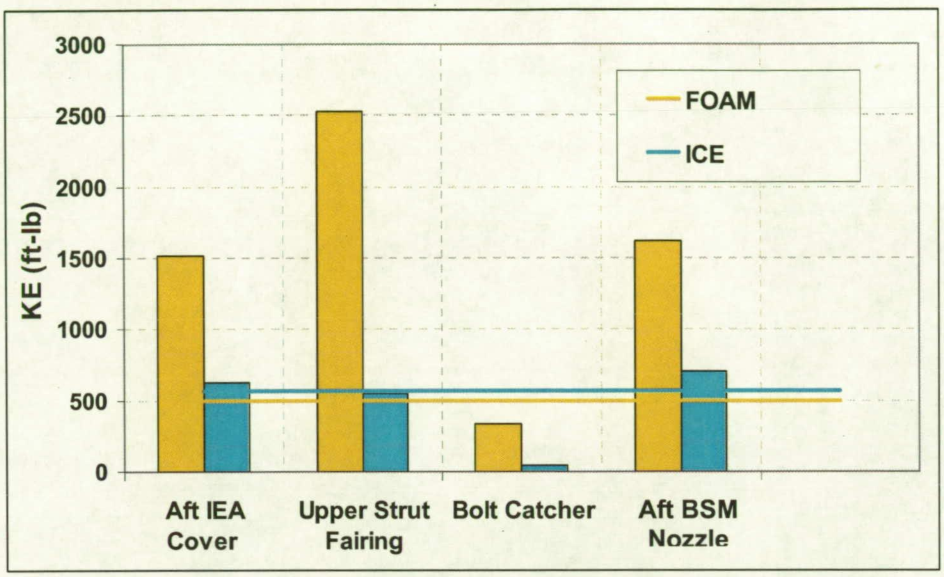



**Figure 17. Sample of Launch Support Debris Analysis Tool**

### 4.3 What Impact Did the Project Have on the Organization

The primary goal of this project was to support RTF by defining the SRB debris environment and hardware capability. The team received approval for their analysis from the Space Shuttle Program management and supported the Shuttle launch on July 26, 2005. Additionally, the team incorporated USA's corporate goals of safety, customer satisfaction, professional development and financial accountability throughout the entire project. Each of these goals was addressed, incorporated, and impacted by the team's project.

Safety - Ensuring safety was achieved by verifying that all SRB hardware would still function as designed after being impacted by foam and ice debris. In addition to evaluating the initial survivability to the debris impact, the structural and thermal loading through SRB separation were also analyzed to verify that the damage would not propagate and reach an unacceptable level. Following USA-SRB Element procedures, all models and analyses were thoroughly reviewed to ensure they were technically sound and accurate. The testing and modeling verified that all critical components would function as expected, and the safety of the mission and crew would not be compromised. Despite the fact that no components had an unacceptable margin, four design changes were incorporated to further reduce the risk that a debris impact might have on a critical system. Additionally, the development of the launch support debris analysis tools allowed for assessment of potential debris sources on the day of launch to verify that the launch would be safe and successful.

Customer Satisfaction - Excellent customer satisfaction and quality were achieved by maintaining a high level of stakeholder involvement throughout the process. Test plans, material models, and impact analysis results were continually reported to and approved by various stakeholders. Each individual test received the approval of quality engineering and correlation

studies were only conducted on test shots meeting specific standards. Team members met on several occasions to verify that all critical hardware were analyzed and there were no additional concerns that might have been overlooked. Also, all models and analyses were put through an internal checking process as part of the modeling correlation hardware evaluations tasks. USA-SRB Element met all stacking and launch milestones associated with RTF. The efforts put forth by the debris team were cited by NASA in award fee evaluations as an "example of outstanding RTF support" and an "area of superb performance."

Professional Development - This project offered team members a new and challenging problem that provided the opportunity to improve their skills and develop their experience base. The tasks of this project required innovative solutions that were best accomplished through advanced analysis techniques and the use of specialized software programs that were new to the organization. All team members who worked on the model correlation and hardware evaluation tasks were provided with advanced training in LS-DYNA. Team members became more familiar with SRB thermal protection systems, hardware, and hardware functions, and now have a solid experience base with new skills that can be used to solve future engineering challenges.

Fiscal Accountability - The financial returns of this project exist as a cost savings to USA and NASA. The work performed was done as efficiently as possible in several ways. During testing the team established minimum criteria of success so that once a sufficient amount of data had been collected, additional planned tests did not need to be performed. Additional testing related costs were alleviated through this technique by reducing the number of flight hardware articles expended. Additionally, computer simulations were used instead of testing all flight hardware, resulting in a significant savings of both time and money. Whenever possible, data from existing computer models was used to reduce analysis time and costs, and any new computer models that were built can be used in future analyses.

Sustaining actions were developed to enable continued safe and efficient operations. The launch support tools were used to support several launch simulations and the RTF Shuttle launch, and will continue to be used to assess potential debris sources on launch day. The tool will continue to provide USA-SRB Element with the ability to make a quick assessment for debris concerns raised on the launch pad. Additionally, the skills developed by team members will be a valuable asset to USA, NASA and the Space Shuttle Program.

The debris team is not willing to rest on developments that have been made. Any design changes or additional new hardware that can be considered debris impact sensitive will be addressed using the same exacting techniques. The launch support tools can also be improved dramatically. The quick assessment currently uses results from the defined debris environment to establish verified limits. The modeling efforts and the launch support tool can be expanded to include absolute upper limits of the hardware capability. As the space program transitions into the next generation vehicle, the SRBs will continue to play a key role. The tools and abilities developed during this task will prove valuable in the future.